

Squark Flavor Implications from $\bar{B} \rightarrow \bar{K}^{(*)}l^+l^-$

Arnd Behring^a, Christian Gross^{a,b}, Gudrun Hiller^a and Stefan Schacht^a

^a*Institut für Physik, Technische Universität Dortmund, D-44221 Dortmund, Germany*

^b*Département Physik, Universität Basel, CH-4056 Basel, Switzerland*

Abstract

Recent experimental and theoretical progress regarding $\bar{B} \rightarrow \bar{K}^{(*)}l^+l^-$ decays led to improved bounds on the Wilson coefficients C_9 and C_{10} of four-fermion operators of the $|\Delta B| = |\Delta S| = 1$ effective Hamiltonian. We analyze the resulting implications on squark flavor violation in the MSSM and obtain new constraints on flavor-changing left-right mixing in the up-squark-sector. We find the dimensionless flavor mixing parameter $(\delta_{23}^u)_{LR}$, depending on the flavor-diagonal MSSM masses and couplings, to be as low as $\lesssim 0.1$. This has implications for models based on radiative flavor violation and leads to $\mathcal{B}(\bar{B}_s \rightarrow \mu^+\mu^-) \gtrsim 1 \times 10^{-9}$. Rare top decays $t \rightarrow c\gamma, t \rightarrow cg, t \rightarrow cZ$ have branching ratios predicted to be below $\lesssim \text{few} \times 10^{-8}, 10^{-6}$ and 10^{-7} , respectively.

1 Introduction

Heavy flavor physics is rapidly advancing with the successful start of the Large Hadron Collider's (LHC) b -physics program and the final analyses from the Tevatron as well as the B -factory experiments Belle and BaBar. Most notably the LHCb collaboration is currently making a clean sweep in model space around the Standard Model (SM): The current upper limit on the $\bar{B}_s \rightarrow \mu^+ \mu^-$ branching ratio at 95% (90%) C.L. [1]

$$\mathcal{B}(\bar{B}_s \rightarrow \mu^+ \mu^-) < 4.5 (3.8) \times 10^{-9} \quad (1)$$

is down to the level of the SM, $\mathcal{B}(\bar{B}_s \rightarrow \mu^+ \mu^-)_{\text{SM}} \sim (2.5 - 4) \times 10^{-9}$, e.g., [2, 3]. The SM prediction is much more precise assuming the measured $B_s - \bar{B}_s$ mass difference to be SM-like, $\mathcal{B}(\bar{B}_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9}$ [4]. Another milestone constitutes the preliminary measurement of the position of the zero of the forward-backward asymmetry in $\bar{B} \rightarrow \bar{K}^{0*} \mu^+ \mu^-$ decays [5]

$$q_0^2 = 4.9_{-1.3}^{+1.1} \text{ GeV}^2, \quad (2)$$

consistent with the SM prediction $q_0^2|_{\text{SM}} = 4.0 \pm 0.3 \text{ GeV}^2$ [6], also [7, 8].

In this work we aim at investigating the space for supersymmetric flavor physics in the light of the recent and new data from direct collider searches and on flavor-changing rare processes $b \rightarrow s l^+ l^-$. Especially, the study of the exclusive modes $\bar{B} \rightarrow \bar{K}^{(*)} \mu^+ \mu^-$, which are accessible to hadron colliders, has progressed significantly over the last year(s) both experimentally and theoretically. The latter is due to the exploitation of the region where the invariant mass of the dilepton is large, of the order of the b -quark mass [9], by making use of the heavy quark effective theory framework of Ref. [10]. Using the recent data from CDF [11] and LHCb [12], improved model-independent constraints on the Wilson coefficients $C_{9,10}$ of the semileptonic four-fermion operators O_9 and O_{10} have been obtained [6, 13].

Here, we study the implications of these $C_{9,10}$ -constraints on squark flavor violation in the minimal supersymmetric SM (MSSM). Flavor violation in supersymmetric (SUSY) models originates from generational mixings in the sfermion mass matrices. One-loop SUSY effects including their phenomenology in semileptonic B -decays are known for a while [14–17]. We work out the implications of the improved data on semileptonic decays, taking into account the recent direct search limits on SUSY particles.

The plan of this paper is as follows: In Section 2 we explain, after introducing the $|\Delta B| = 1$ effective theory framework, why only chirality-flipping flavor mixing between the second and third generation in the up-sector, parametrized as $(\delta_{23}^u)_{LR}$, has a significant sensitivity to the $C_{9,10}$ -constraints. We then describe the method of SUSY parameter scanning and discuss the constraints on $(\delta_{23}^u)_{LR}$. Results are given in Section 3, including predictions for b -physics, implications for the models with radiative flavor violation (RFV) recently discussed in Refs. [18, 19], and rare top decays. We summarize in Section 4. Details on the SUSY loop contributions to $b \rightarrow s l^+ l^-$ processes including corrections to the literature are given in the Appendix.

2 Constraining squark flavor mixing

In Section 2.1 the effective theory for $|\Delta B| = 1$ transitions is described. In Section 2.2 we discuss which flavor parameters in supersymmetric models can be effectively probed in semileptonic decays. The constraints are worked out in Section 2.3, and discussed in Section 2.4.

2.1 The $|\Delta B| = 1$ effective theory framework

In order to describe rare decays of B -mesons, we employ the effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu) + \text{h.c.} , \quad (3)$$

where the C_i are Wilson coefficients and the O_i higher-dimensional $|\Delta B| = |\Delta S| = 1$ operators, and V denotes the Cabibbo-Kobayashi-Maskawa (CKM) matrix, G_F the Fermi constant and μ the factorization scale. The New Physics (NP) contribution to the current-current ($O_{1,2}$), QCD penguin (O_{3-6}) and chromomagnetic dipole (O_8) operators can be neglected here (cf., e.g., [14]). The most relevant operators are the electromagnetic dipole operator O_7 and the semileptonic four-fermion operators $O_{9,10}$, written as

$$\begin{aligned} O_7 &= \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu} , \\ O_9 &= \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L) (\bar{l} \gamma^\mu l) , & O_{10} &= \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L) (\bar{l} \gamma^\mu \gamma_5 l) . \end{aligned} \quad (4)$$

The $\overline{\text{MS}}$ mass of the b -quark is denoted by m_b , and we neglect the mass of the strange quark.

In general models for NP, the effective Hamiltonian contains additional operators with flipped chirality. In the SM and in minimally flavor-violating (MFV) SUSY models with CKM-induced flavor violation, these are suppressed by m_s/m_b compared to the corresponding unflipped operators given in Eq. (4). The non-MFV chargino contributions to $b \rightarrow sl^+l^-$ processes share this feature of suppressed chirality-flipped contributions. As discussed below, we will be mainly interested in chargino loop-induced contributions, so it is justified to neglect the chirality-flipped operators and consider left-handed currents only. Furthermore, we do not take into account the effects of the scalar- and pseudoscalar semileptonic operators (and their chirality-flipped counterparts). This is a good approximation for not too large $\tan \beta$ [20], to which we restrict our analysis. The exclusion of a sizable enhancement in the $\bar{B}_s \rightarrow \mu^+ \mu^-$ branching ratio, see Eq. (1), supports this further.

The NP contribution, which in our case is the MSSM contribution, can be split into one stemming from the diagonal elements of the squark mass matrices, labeled 'diag', and the remainder induced by the corresponding flavor off-diagonal entries as

$$C_i^{\text{NP}} = C_i^{\text{diag}} + C_i^{\text{MI}} , \quad (5)$$

m_t^{pole}	173.3 GeV	[25]
$m_b(m_b)$	4.19 GeV	[26]
m_W	80.399 GeV	[26]
m_Z	91.1876 GeV	[26]
$\alpha_s(m_Z)$	0.1184	[26]
s_W^2	0.23116	[26]

Table 1: The values of the Standard Model parameters used in this work.

where C_i^{NP} denotes the NP contribution to the C_i , i.e., $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$. We use the terminology ‘mass insertion’ (MI) since we will constrain the commonly used MI parameters, i.e., the off-diagonal elements of the squark mass term divided by an average squark mass squared. Note, however, that we do not rely on the MI approximation [21, 22] in the numerical analysis, but instead use the exact formulae.

We employ the two-loop matching conditions of Ref. [23] for the SM contribution and the one-loop results of [14–16] for the MSSM contribution. The Wilson coefficients at the relevant scale for b -decays, $\mu_b = \mathcal{O}(m_b)$, are obtained from the ones at the matching scale μ_0 of $\mathcal{O}(100 \text{ GeV})$ by solving the RG equations. We perform this by extending and using the flavor tool EOS [24]. The values of the SM parameters used are given in Table 1. The SM values of the most important Wilson coefficients are given as (at $\mu_b = 4.2 \text{ GeV}$)

$$C_7^{\text{SM}}(\mu_b) = -0.33, \quad C_9^{\text{SM}}(\mu_b) = 4.27, \quad C_{10}^{\text{SM}}(\mu_b) = -4.15. \quad (6)$$

2.2 SUSY flavor contributions to $b \rightarrow sl^+l^-$

We begin by discussing which MI parameters have the best potential of receiving significantly improved constraints from the $C_{9,10}$ -bounds. Relevant for $C_{9,10}$ are $(\delta_{23}^d)_{LL}$ and $(\delta_{23}^d)_{LR}$, which enter through gluino loops, and $(\delta_{23}^u)_{LL}$ and $(\delta_{23}^u)_{LR}$, which appear in chargino loops. Of these, the ones which are not yet very much constrained by bounds on other Wilson coefficients (C_7 in this case) and at the same time give a substantial contribution to $C_{9,10}$ are most interesting:

- The parameter $(\delta_{23}^d)_{LR}$ is already tightly constrained by bounds on C_7 from data on the $\bar{B} \rightarrow X_s \gamma$ branching ratio [22]. In addition, $(\delta_{23}^d)_{LR}$ contributes to $C_{9,10}$ only in double MI diagrams [16]. We conclude that it plays no role for our analysis.
- The parameter $(\delta_{23}^d)_{LL}$ is much less constrained by $\bar{B} \rightarrow X_s \gamma$ and $B_s - \bar{B}_s$ mixing [27] than $(\delta_{23}^d)_{LR}$. On the other hand, $(\delta_{23}^d)_{LL}$ has little effect on $C_{9,10}$: Its effect in the Z -penguin gluino loop is suppressed with respect to that in the γ -penguin by a factor of m_b^2/m_Z^2 (as discussed, e.g., in [16]). The γ -penguin in turn does not contribute at all to C_{10} , and its contribution to C_9 is numerically

m_{H^\pm}	$\tan \beta$	M_2	μ	$m_{\tilde{t}_R}$	$m_{\tilde{q}}$	A_t	$m_{\tilde{\nu}}$	$m_{\tilde{g}}$
300	4	150	-300	300	1000	1000	100	700

Table 2: Example SUSY point at $\mu_0 = 120$ GeV. All masses are in GeV. $m_{\tilde{q}}, m_{\tilde{t}_R}$ are the diagonal elements of the squark mass matrix as given in the Appendix. The point corresponds to the following spectrum: $m_{\tilde{t}_1} = 236$ GeV, $m_{\tilde{t}_2} = 1017$ GeV, $m_{\tilde{\chi}_1} = 150$ GeV, $m_{\tilde{\chi}_2} = 321$ GeV and $m_{h^0} = 117$ GeV.

$C_7^{\text{MI},\tilde{\chi}}(\mu_0)$	$C_9^{\text{MI},\tilde{\chi}}(\mu_0)$	$C_{10}^{\text{MI},\tilde{\chi}}(\mu_0)$
$0.01(\delta_{23}^u)_{LR} - 0.38(\delta_{23}^u)_{LL}$	$0.17(\delta_{23}^u)_{LR} - 0.11(\delta_{23}^u)_{LL}$	$-2.24(\delta_{23}^u)_{LR} + 0.19(\delta_{23}^u)_{LL}$
$C_7^{\text{MI},\tilde{g}}(\mu_0)$	$C_9^{\text{MI},\tilde{g}}(\mu_0)$	$C_{10}^{\text{MI},\tilde{g}}(\mu_0)$
$16.35(\delta_{23}^d)_{LR} - 0.02(\delta_{23}^d)_{LL}$	$0.04(\delta_{23}^d)_{LL}$	—

Table 3: Flavor off-diagonal Wilson coefficients at $\mu_0 = 120$ GeV for the SUSY point given in Table 2. Double mass insertions are not shown.

subleading to those from chargino loops, in particular for squark masses above a TeV. Therefore, the parameter $(\delta_{23}^d)_{LL}$ is not of interest to our study.

- The coefficients $(\delta_{23}^u)_{LL}$ and $(\delta_{23}^u)_{LR}$ both give a non-negligible contribution to C_7 , which is, however, by far not as significant as that from $(\delta_{23}^d)_{LR}$. The impact of $(\delta_{23}^u)_{LX}$, $X = L, R$ contributions to $B_s - \bar{B}_s$ mixing is very small and negligible [27]. As exemplified in Table 3 for the SUSY benchmark point given in Table 2, $(\delta_{23}^u)_{LL}$ gives a much larger contribution to C_7 than $(\delta_{23}^u)_{LR}$. Moreover, C_{10} is about an order of magnitude more sensitive to $(\delta_{23}^u)_{LR}$ than to $(\delta_{23}^u)_{LL}$. We conclude that $(\delta_{23}^u)_{LR}$ is the most relevant parameter for our analysis on updated constraints from $C_{9,10}$ -bounds.

For completeness and because of disagreement with the literature in the photon-penguin [16], see Appendix, we give here the dependence of $C_{7,9,10}$ on $(\delta_{23}^u)_{LR}$ in the MI approximation,

$$\begin{aligned}
C_7^{\text{MI},\tilde{\chi}}(\mu_0) &= \frac{V_{cs}^*}{V_{ts}^*} \frac{\lambda_t}{g_2} \frac{m_W^2}{m_{\tilde{q}}^2} F \times (\delta_{23}^u)_{LR}, \\
C_9^{\text{MI},\tilde{\chi}}(\mu_0) &= \frac{V_{cs}^*}{V_{ts}^*} \frac{1}{4 s_W^2} \frac{\lambda_t}{g_2} \left((4s_W^2 - 1) F^{Z\text{-p}} + 4s_W^2 \frac{m_W^2}{m_{\tilde{q}}^2} F^{\gamma\text{-p}} - \frac{m_W^2}{m_{\tilde{q}}^2} F^{\text{box}} \right) (\delta_{23}^u)_{LR}, \\
C_{10}^{\text{MI},\tilde{\chi}}(\mu_0) &= \frac{V_{cs}^*}{V_{ts}^*} \frac{1}{4 s_W^2} \frac{\lambda_t}{g_2} \left(F^{Z\text{-p}} + \frac{m_W^2}{m_{\tilde{q}}^2} F^{\text{box}} \right) (\delta_{23}^u)_{LR},
\end{aligned} \tag{7}$$

where λ_t denotes the top Yukawa coupling and s_W^2 the sine squared of the weak mixing angle. The expressions F and $F^{\gamma\text{-p}}$ are due to γ -penguin-diagrams, while $F^{Z\text{-p}}$ and F^{box} are due to Z -penguin- and box-diagrams, respectively. Their explicit form can be found in the Appendix. The up-squarks are assumed to be roughly degenerate, except for the right-handed stop, which is allowed to be significantly lighter. Notice that the γ -penguin and box-contributions are parametrically suppressed by $m_W^2/m_{\tilde{q}}^2$ with

respect to the Z -penguin effect. Furthermore, since the Z -boson mainly has an axial-vector coupling to charged leptons, the Z -penguin contribution to C_9 is suppressed to the one to C_{10} by $|4s_W^2 - 1| \ll 1$ [28].

2.3 Numerical analysis

For the numerical analysis we scan the SUSY parameter space within the ranges given in Table 4. All parameters are assumed to be at the electroweak scale, taken to be $\mu_0 = 120$ GeV. We fix the lightest sneutrino mass $m_{\tilde{\nu}} = 100$ GeV because the dependence of $C_{9,10}^{\text{NP}}$ on $m_{\tilde{\nu}}$ is very mild only. We denote by $m_{\tilde{q}}^2$ the k th, $k = 1, \dots, 5$ diagonal element of the up-squark mass matrix and by $m_{\tilde{t}_R}^2$ the remaining diagonal entry connected to the right-handed stop, including the F and D terms, see Appendix. We further fix $m_{\tilde{q}} = 1000$ GeV because the bounds can get only weaker for larger average squark masses. All flavor-violating MI parameters except for $(\delta_{23}^u)_{LR}$ are set to zero.

Then, for each parameter point we require the following constraints to be satisfied:

- i)* The bounds from the $\bar{B} \rightarrow X_s \gamma$ branching ratio: $0.3 \leq |C_7(\mu_b)| \leq 0.4$ [6], see text.
- ii)* The lightest chargino mass limit: $m_{\chi_1^\pm} \geq 94$ GeV [26].
- iii)* The lightest stop mass limit $m_{\tilde{t}_1} \geq 100$ GeV from DØ [29]. We choose this lower bound since the stronger one from CDF, $m_{\tilde{t}_1} \geq 180$ GeV [30], assumes the stop predominantly decaying via charged currents to b -quarks, a lepton and missing energy. The recent LHC findings [31,32] are model-dependent, too, and not taken into account here.
- iv)* The Higgs mass limits: $m_{h^0} \geq 114.4$ GeV [26] and $m_{A^0} \geq 200$ GeV. We require the latter to ensure that h^0 is sufficiently SM-like, see text.
- v)* Electroweak precision tests: $-0.0007 \leq \Delta\rho \leq 0.0017$ [26].

	$\tan \beta$	m_{H^\pm}	M_2	$ \mu $	$m_{\tilde{t}_R}$	A_t	$(\delta_{23}^u)_{LR}$
min.	3	300	100	80	170	-3000	-0.85
max.	15	1000	1000	1000	800	3000	0.85

Table 4: Ranges of the SUSY parameters (at $\mu_0 = 120$ GeV) used for the parameter scan, see text. All masses are in GeV. We fix $m_{\tilde{\nu}} = 100$ GeV and $m_{\tilde{q}} = 1000$ GeV.

The MSSM allows for large contributions to C_7 , which can flip its sign while still being in agreement with data, see *i)*. However, the existence of a zero-crossing of the forward-backward asymmetry in $\bar{B} \rightarrow \bar{K}^* \mu^+ \mu^-$, see Eq. (2), enforces $\text{sign}(C_7 C_9)$ to be SM-like. Since C_9 cannot change sign within the MSSM [17], we allow in our analysis only MSSM points with SM-like signed C_7 .

We use the **FeynHiggs** code [33–36] v.2.9.0-beta¹ to check iv) and v). Further, we add 3 GeV to the prediction for m_{h^0} in order to account for the theoretical uncertainty [35]. Note further that the recent 95% C.L. exclusion limits for a SM-like Higgs boson from ATLAS and CMS suggest a valid range around $(125 \pm \text{few})$ GeV [37, 38]. We checked that while such values require typically larger A_t than the constraint iv), the generic features of our flavor analysis hold.

Throughout this work we choose the normalization $(\delta_{23}^u)_{LR} = (\Delta_{23}^u)_{LR} / \overline{M}_u^2$, where $\overline{M}_u^2 = (\frac{5}{6}m_{\tilde{q}}^2 + \frac{1}{6}m_{\tilde{t}_R}^2)$ to connect the dimensionless MI parameter $(\delta_{23}^u)_{LR}$ to the off-diagonal element $(\Delta_{23}^u)_{LR}$ of the up-squark mass matrix in the super-CKM basis. Note that values of $(\delta_{23}^u)_{LR}$ outside the range given in Table 4 would yield tachyonic squarks due to the large, order one off-diagonal entry. Note also that a normalization to the geometric mean of the diagonal entries would result in increasingly larger values of $(\delta_{23}^u)_{LR}$ for lighter right-handed stops $m_{\tilde{t}_R} < m_{\tilde{q}}$.

We begin by assuming flavor-diagonal SUSY contributions only, i.e., for $(\delta_{23}^u)_{LR} = 0$. In this case charged Higgs boson and CKM-driven chargino loops give non-vanishing NP contributions to the Wilson coefficients. Defining the ratios

$$R_i \equiv \left| \frac{C_i^{\text{NP}}}{C_i^{\text{SM}}} \right| \quad (8)$$

we find the following, maximally possible NP effects

$$R_9(\mu_b) \lesssim 3\%, \quad R_{10}(\mu_b) \lesssim 11\% . \quad (\text{MFV}) \quad (9)$$

As expected [17], the flavor-diagonal SUSY effects on $C_{9,10}$ are small and well within what is allowed by present and near-future data.

Switching on squark flavor violation, the possible size of NP effects in the Wilson coefficients increases

$$R_9(\mu_b) \lesssim 4\%, \quad R_{10}(\mu_b) \lesssim 47\% , \quad (\text{no s.l. bounds}) \quad (10)$$

in particular in C_{10} . Here, the new semileptonic bounds are not yet taken into account. Note that the Higgs mass bound iv) is efficient, as previously noted in [39]; if ignored, the allowed range for $R_{10}(\mu_b)$ would be more than a factor of two larger.

The outcome of the full scan is shown in Fig. 1: SUSY points that pass i) - v) are shown together with the allowed regions (gray areas) in the $C_9(\mu_b) - C_{10}(\mu_b)$ plane from the recent analysis of $\bar{B} \rightarrow \bar{K}^{(*)}l^+l^-$ decays [6] for SM-like signed C_7 . The SUSY flavor effects are dominated by the Z -penguin contribution, correlating C_9 and C_{10} as $C_{10}^{Z-P}/C_9^{Z-P} = 1/(4s_W^2 - 1)$, see Eq. (7). The latter correlation is shown as the dotted line and is clearly featured by the model. The analogous solutions with flipped-sign $C_7 > 0$, which are allowed model-independently [6], are excluded in the MSSM (and not shown): firstly because the Z -penguin dominated scatter points miss in this case the allowed $C_9(\mu_b) - C_{10}(\mu_b)$ parameter space and secondly because of the measurement Eq. (2).

¹We are grateful to Sven Heinemeyer for **FeynHiggs** support and provision of version 2.9.0-beta.

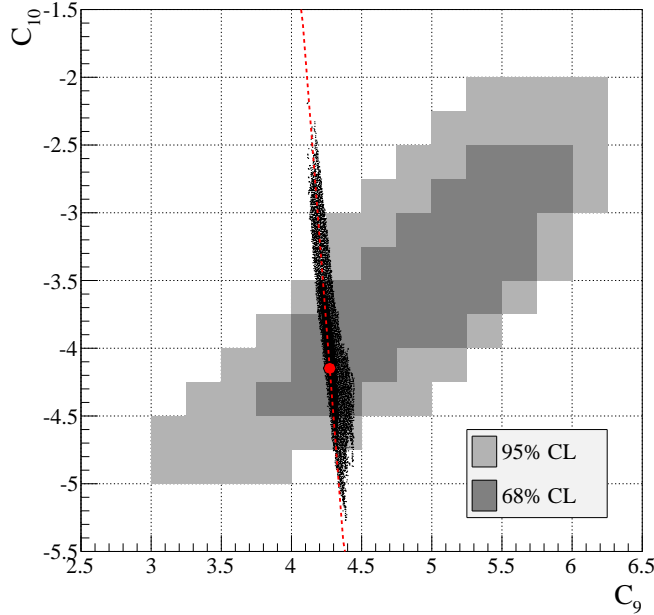


Figure 1: Reach of SUSY models with $(\delta_{23}^u)_{LR} \neq 0$ in the $C_9(\mu_b)$ – $C_{10}(\mu_b)$ plane for $C_7(\mu_b) < 0$. The light (dark) gray shaded areas are the 95% (68%) confidence limit bounds which were obtained from $B \rightarrow K^{(*)}l^+l^-$ data in Fig. 7 of Ref. [6]. The red dotted line denotes the Z -penguin correlation $C_{10}^{Z-P}/C_9^{Z-P} = 1/(4s_W^2 - 1)$. The SM point $(C_9^{\text{SM}}, C_{10}^{\text{SM}})$ is marked by the red dot.

Including the semileptonic decay data at 68% (95%) C.L. we obtain

$$R_9(\mu_b) \lesssim 4\% \text{ (4\%)}, \quad R_{10}(\mu_b) \lesssim 16\% \text{ (28\%)}, \quad (11)$$

cutting into the models' parameter space, cf. Eq. (10). Due to the Z -penguin dominance of the SUSY flavor contributions to C_9 and C_{10} , the constraints Eq. (11) are much stronger than those on model-independent scenarios with general C_9 and C_{10} [6].

2.4 Constraining $(\delta_{23}^u)_{LR}$

Previous works found that $(\delta_{23}^u)_{LR}$ is essentially unconstrained by $|\Delta B| = |\Delta S| = 1$ decay data [40]. We illustrate the impact of the new constraints from semileptonic decays on squark flavor mixing. In Fig. 2 we show the upper limit on $|(\delta_{23}^u)_{LR}|$, without (left-hand plot) and including (right-hand plot) the recent data on semileptonic decays. For the latter plot we employ the 68% C.L. bounds that are depicted in dark gray in Fig. 1. For definiteness, we choose the A_t – $m_{\tilde{t}_R}$ plane around the SUSY parameter point defined in Table 2. One observes that, at least in this part of the SUSY parameter space, the bound on $(\delta_{23}^u)_{LR}$ is significantly improved by the new data.

In Fig. 3 we show the upper limits on $|(\delta_{23}^u)_{LR}|$ in the μ – M_2 and the $m_{\tilde{t}_R}$ – $\tan \beta$ plane, in both cases including the data from $\bar{B} \rightarrow \bar{K}^{(*)}l^+l^-$. The bounds grow stronger

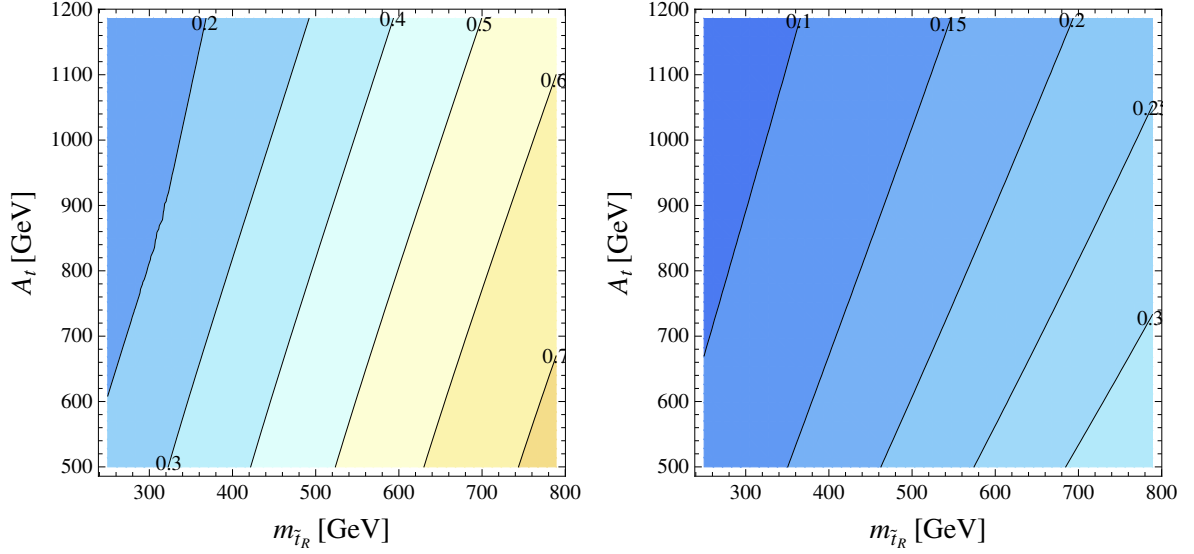


Figure 2: Upper bounds on $|(\delta_{23}^u)_{LR}|$ around the SUSY parameter point defined in Table 2. Left-hand side: without semileptonic bounds. Right-hand side: including the semileptonic bounds at 68% C.L.

for decreasing M_2 and decreasing $m_{\tilde{t}_R}$. Note that the Higgs mass limits and bounds by electroweak precision tests are discarded in Figs. 2 and 3, as we only want to show here the parametric dependence of the new semileptonic bounds.

Note that $(\delta_{23}^u)_{LR}$ is also constrained by demanding vacuum stability,

$$(\delta_{23}^u)_{LR} \leq \frac{m_t}{\overline{M}_u^2} \sqrt{2\overline{M}_u^2 + \overline{M}_l^2}, \quad (12)$$

where \overline{M}_u^2 and \overline{M}_l^2 denote an averaged up-squark and slepton mass squared, respectively [41]. Requiring only metastability, these bounds are in general weakened but only very little so in case of $(\delta_{23}^u)_{LR}$ [42]. Depending on the flavor-diagonal MSSM parameters, the bounds on $(\delta_{23}^u)_{LR}$ from $\bar{B} \rightarrow \bar{K}^{(*)} l^+ l^-$ data which we obtain are stronger than the vacuum stability bounds. For instance, setting $m_{\tilde{q}} = m_{\tilde{l}} = 1$ TeV and $m_{\tilde{t}_R} = 300$ GeV, vacuum stability requires $(\delta_{23}^u)_{LR} \lesssim 0.3$, which is comparable to the bounds shown in the left-hand plot of Fig. 2 but weaker than the ones in the right-hand plot, which includes the new semileptonic rare decay data.

3 Predictions

We present implications for b -physics in Section 3.1, for RFV models in Section 3.2 and for rare decays of the top in Section 3.3.

3.1 b -physics

The constraints Eq. (11) imply upper bounds on CP phases of the same order in the respective Wilson coefficients assuming order one phases in the flavor parameter

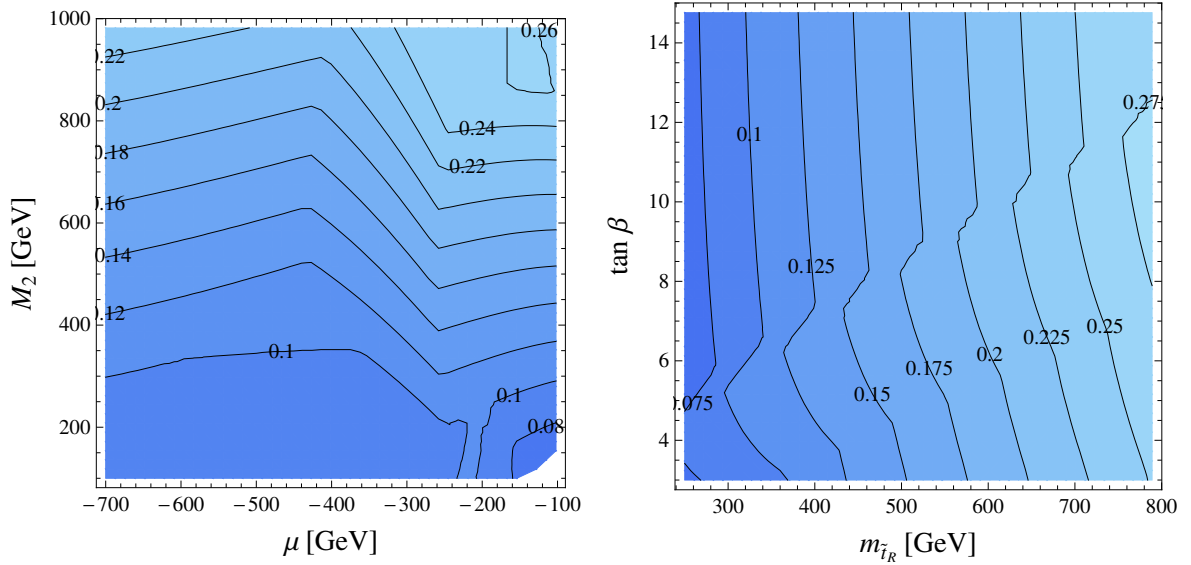


Figure 3: Upper bounds on $|(\delta_{23}^u)_{LR}|$ around the SUSY point given in Table 2, varying in different directions around the example SUSY parameter point. Both plots include the 68% C.L. semileptonic bounds.

$(\delta_{23}^u)_{LR}$. Only little is known to date about the CP-violating phases of $C_{9,10}$: the relative phase $|\arg C_9 C_{10}^*|$ is constrained by data on $\bar{B} \rightarrow \bar{K}^* l^+ l^-$ decays at large dilepton masses to be near π [43]. The situation will improve in the future with more precise data and measurements of CP asymmetries. Specifically the (naive) T-odd CP asymmetry $\langle A_7^D \rangle$ is unsuppressed by strong phases [44] and is directly sensitive to CP violation in C_{10} and hence SUSY flavor. At large dilepton masses the CP asymmetry $\langle a_{CP}^{(3)} \rangle$ [43] is promising. The latter is related to the CP asymmetry of the forward-backward asymmetry put forward in Ref. [28].

We predict from Fig. 1 that the $\bar{B}_s \rightarrow \mu^+ \mu^-$ branching ratio $\mathcal{B}(\bar{B}_s \rightarrow \mu^+ \mu^-) \propto f_{\bar{B}_s}^2 |C_{10}|^2$ is enhanced (suppressed) with respect to the SM one by at most a factor of 1.3 (0.5) at 95% C.L. and within the range

$$1 \times 10^{-9} \lesssim \mathcal{B}(\bar{B}_s \rightarrow \mu^+ \mu^-) < 5(6) \times 10^{-9}. \quad (13)$$

On the other hand, taking the recent upper limit Eq. (1) one obtains at 95% C.L. ²

$$R_{10}(\mu_b) \lesssim 46\% \text{ (20\%)}, \quad (14)$$

consistent with Eq. (11). In Eqs. (13) and (14) we used for the B_s -meson's decay constant $f_{B_s} = 231(15)(4)$ MeV from Ref. [46], corresponding to a SM branching ratio $\mathcal{B}(\bar{B}_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.1 \pm 0.6) \times 10^{-9}$. The numbers in parentheses correspond to $f_{B_s} = 256(6)(6)$ MeV from Ref. [47], with $\mathcal{B}(\bar{B}_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.8 \pm 0.4) \times 10^{-9}$. In the lattice results the first error is statistical and the second one from systematics.

²It has been pointed out recently [45] that the finite lifetime difference in the B_s -system causes $\mathcal{B}(\bar{B}_s \rightarrow \mu^+ \mu^-)$ when extracted from an untagged measurement as in Eq. (1) to differ from its corresponding value in the unmixed case. Including the effects from mixing, the limits in Eq. (14) would get stronger by a few percent.

One observes that the purely leptonic and the semileptonic decays give about comparable constraints. Since the former has a larger sensitivity to scalar/pseudoscalar operators, which would in SUSY kick in for large values of $\tan\beta$ and a not too heavy Higgs sector and which we neglect, the combined analysis of both modes is most important as they probe complementary NP.

Furthermore, the forward-backward asymmetry in $\bar{B} \rightarrow \bar{K}^* l^+ l^-$ decays exhibits a well-known zero in the SM, roughly determined by $-2m_b m_B \text{Re}(C_7(\mu_b)/C_9(\mu_b))$. In the SUSY model both C_7 and C_9 are near their respective SM values, and so is the location of the zero. This is consistent with data, cf. Eq. (2).

3.2 Implications for RFV models

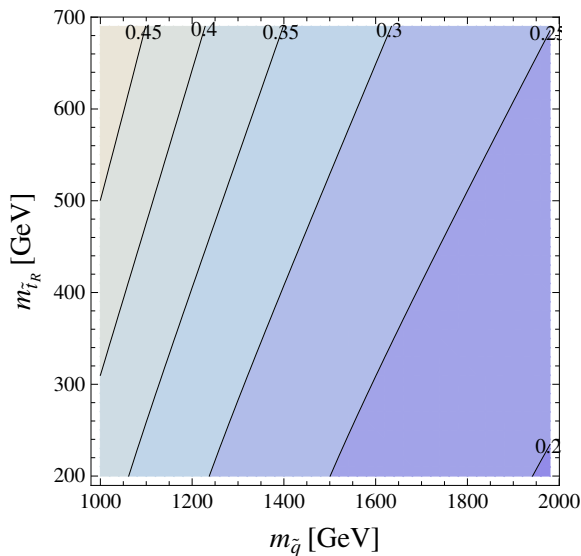


Figure 4: The required value of $(\delta_{23}^u)_{LR}$ in the RFV model, see Eq. (15), for $m_{\tilde{g}} = 1000$ GeV and $(\delta_{23}^d)_{LR} = 0$.

As shown in Section 2.4, the current bounds on $(\delta_{23}^u)_{LR}$ can reach a level of ~ 0.1 . This implies constraints on SUSY flavor models which have rather largish values of $(\delta_{23}^u)_{LR}$ in this ballpark. One such model [18, 19] (see references therein for earlier works) is based on radiative flavor violation, where the small fermion masses and CKM off-diagonal elements originate from quantum loops [48]. The CKM matrix is assumed to be the unit matrix at tree level, and the off-diagonal elements are induced by quantum corrections involving off-diagonal trilinear SUSY breaking couplings. Specifically, the quark mixing between the second and the third generation is then given as [18, 19]

$$V_{cb} = \frac{2\alpha_s}{3\pi m_{\tilde{g}}} \left(\frac{(\Delta_{23}^d)_{LR}}{m_b} \tilde{C}_0(x, x) - \frac{(\Delta_{23}^u)_{LR}}{m_t} \tilde{C}_0(x, y) \right), \quad (15)$$

where $x = m_{\tilde{q}}^2/m_{\tilde{g}}^2$ and $y = m_{\tilde{t}_R}^2/m_{\tilde{g}}^2$ and

$$\tilde{C}_0(x, y) = \frac{(1-y)x \log(x) + (x-1)y \log(y)}{(x-1)(y-1)(x-y)}. \quad (16)$$

The dimensionless loop function \tilde{C}_0 satisfies $\tilde{C}_0(1, 1) = -1/2$ and $\tilde{C}_0(1, 0) = -1$. Above, we allowed for an admixture of flavor generation from squark mixing in the down-sector $(\delta_{23}^d)_{LR} = (\Delta_{23}^d)_{LR}/m_{\tilde{q}}^2$ as well.

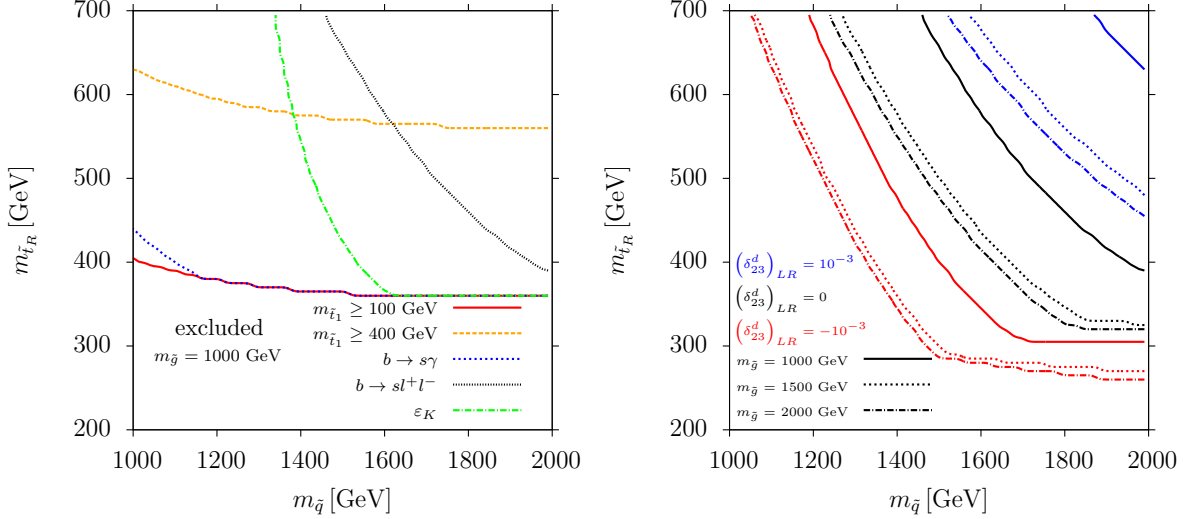


Figure 5: Excluded regions of RfV parameter space in the $m_{\tilde{q}} - m_{\tilde{t}_R}$ plane around the SUSY point given in Table 2 with $M_2 = 800$ GeV. The left-hand plot displays all bounds including the semileptonic bound at 95% C.L. (black line), the limit from $m_{\tilde{t}_1} > 100$ GeV (red line), a hypothetical limit $m_{\tilde{t}_1} > 400$ GeV (orange line), ϵ_K (green line) and $b \rightarrow s\gamma$ (blue line) for $m_{\tilde{g}} = 1000$ GeV and $(\delta_{23}^d)_{LR} = 0$. In the right-hand plot the 95% C.L. semileptonic bounds are shown for different values of $m_{\tilde{g}}$ and in addition with finite $(\delta_{23}^d)_{LR} = \pm 1 \times 10^{-3}$.

From Eq. (15) one can determine the flavor mixings required for a realistic CKM element $V_{cb} = (40.6 \pm 1.3) \times 10^{-3}$ [26]. Since $\tilde{C}_0 < 0$, it follows that $(\delta_{23}^u)_{LR} > 0$ is required, and that an additional contribution from $(\delta_{23}^d)_{LR} > 0$ (< 0) demands a larger (smaller) value for $(\delta_{23}^u)_{LR}$. The value of $(\delta_{23}^u)_{LR}$ required to generate V_{cb} is shown in Fig. 4 for $m_{\tilde{g}} = 1000$ GeV and $(\delta_{23}^d)_{LR} = 0$. We evaluate Eq. (15) at $\mu_0 = 120$ GeV. Since the requisite $(\delta_{23}^u)_{LR}$ is sufficiently below one, at least for the region displayed and for reasonable gluino masses, the use of the mass insertion approximation is justified, see also [19]. For the gluino-down-squark contribution to the Wilson coefficients we use the mass insertion approximation of the exact results given in [14].

We further evaluate the constraints from $K^0 - \bar{K}^0$ -mixing via up-squark mixing with the third generation, induced by $(\delta_{23}^u)_{LR}^* (\delta_{13}^u)_{LR}$. The latter factor has a large CP-phase since $(\delta_{13}^u)_{LR}$ generates V_{ub} through the analogue of Eq. (15) [19]. We use the full, non-MI result given in Ref. [49] with erratum [50] and apply $\epsilon_K^{\text{RFV}} < 0.6 \epsilon_K^{\text{exp}}$.³ We

³We thank Andreas Crivellin for numerical checks of the chargino contribution to $K^0 - \bar{K}^0$ -mixing.

	SM	MSSM pre-LHC	ATLAS 10 fb ⁻¹	ATLAS 100 fb ⁻¹
$t \rightarrow c\gamma$	4.6×10^{-14}	5.2×10^{-7}	9.4×10^{-5}	3.0×10^{-5}
$t \rightarrow cg$	4.6×10^{-12}	3.2×10^{-5}	4.3×10^{-3}	1.4×10^{-3}
$t \rightarrow cZ$	1×10^{-14}	1.8×10^{-6}	4.4×10^{-4}	1.4×10^{-4}

Table 5: The branching ratios of rare top decays in the SM [54, 55] and upper limits in the MSSM from the pre-LHC era [56]. The last two columns denote the ATLAS sensitivity (5σ observation) with 10 fb⁻¹ and 100 fb⁻¹, respectively [57].

use the NLO-RG factor $\eta \simeq 0.8$ [51, 52] for the leading $\Delta F = 2$ operator $[\bar{s}\gamma_\mu(1-\gamma_5)d]^2$ with bag parameter $B_K^{\overline{\text{MS}}}(2 \text{ GeV}) = 0.52$ [53].

The interplay of the various constraints is illustrated in Fig. 5. We show the exclusion regions in the $m_{\tilde{t}_R}$ - $m_{\tilde{q}}$ plane with SUSY parameters chosen around the SUSY point defined in Table 2 with $M_2 = 800 \text{ GeV}$. Note that in the chargino-loop $b \rightarrow sl^+l^-$ amplitude some CKM elements of the Wilson coefficients, see, e.g., Eq. (7) in the MI approximation, cancel against those in Eq. (3) to only diagonal elements $V_{tb}V_{cs}^*$. For those we use the physical CKM matrix elements instead of the bare ones [19]. We find that the constraints from ϵ_K are weaker than the semileptonic bounds for not too small values of M_2 and for stops sufficiently split from the other squarks, around the point Table 2 for $M_2 \gtrsim 500 \text{ GeV}$ and $m_{\tilde{t}_R} \lesssim 800 \text{ GeV}$. In other words, the Glashow-Iliopoulos-Maiani (GIM) suppression can efficiently make evade the semileptonic bounds. We learn that the new $\bar{B} \rightarrow \bar{K}^{(*)}l^+l^-$ data allows to exclude an additional part of the parameter space. The excluded region is larger for lighter gluinos and for contributions from $(\delta_{23}^d)_{LR} > 0$.

3.3 Implications for rare top decays

Since the same flavor-changing squark mass parameters enter B -meson- and top quark decay amplitudes, the improved constraints on $(\delta_{23}^u)_{LR}$ obtained in Section 2 can lead to sharper upper bounds on the branching ratio of rare top decays in the MSSM. Specifically, we consider $t \rightarrow cV$, where V is either a photon, gluon or a Z -boson. In the SM, the branching ratios are negligibly small, related to a GIM suppression [54, 55]. Estimates together with upper limits from a pre-LHC study for the MSSM [56] and the requisite branching ratios for 5σ observations at center-of-mass energy $\sqrt{s} = 14 \text{ TeV}$ with 10 fb⁻¹ and 100 fb⁻¹ of collision data [57] are compiled in Table 5. Thus, an observation of these decays at the LHC is already excluded for the case of the MSSM. In order to further strengthen this point, we nevertheless find it useful to provide updated bounds on the achievable branching ratios in the MSSM.

The leading contributions arise from squark-gluino loops with non-vanishing $(\delta_{23}^u)_{LR}$ and/or $(\delta_{23}^u)_{LL}$. It turns out that the largest effect in the rate into all three final states is due to diagrams involving $(\delta_{23}^u)_{LR}$, cf. [56]. We calculate the branching ratios for each parameter point in the region defined by Table 4 which passes the constraints $i)$ to $v)$ as well as the constraints on C_9 and C_{10} from $\bar{B} \rightarrow \bar{K}^{(*)}l^+l^-$. The gluino mass is taken to be $m_{\tilde{g}} = 700 \text{ GeV}$. For heavier gluinos the upper bounds on the branching

ratios decrease further. We employ the formulae for the $t \rightarrow cV$ decay widths which are found in [58]. The branching ratios are obtained by normalizing $\Gamma(t \rightarrow cV)$ to the SM value for the dominant decay mode of the top quark, $\Gamma(t \rightarrow bW) = 1.29 \text{ GeV}$ [26]. Note that, as in Section 2, we do not rely on the MI approximation.

As a result, we find that the maximal branching ratios compatible with the 68% C.L. constraints from the rare B -decays are

$$\mathcal{B}(t \rightarrow c\gamma) \lesssim 2.1 \times 10^{-8}, \quad \mathcal{B}(t \rightarrow cg) \lesssim 7.2 \times 10^{-7}, \quad \mathcal{B}(t \rightarrow cZ) \lesssim 1.0 \times 10^{-7}. \quad (17)$$

The constraints improve on the ones from a previous pre-LHC study shown in Table 5 by a factor of 24, 44 and 18 for decays to γ, g and Z plus charm, respectively. The improvement is, depending on the parameter point, due to the $\Delta B = 1$ data but also from the improved squark and gluino mass bounds from the LHC. Without the Higgs mass constraint *inv*) enforced using **FeynHiggs** v.2.9.0-beta, the limits in Eq. (17) would be lifted by about $\mathcal{O}(5 - 8)$.

4 Summary

Recent progress in both the theoretical description and the data regarding $\bar{B} \rightarrow \bar{K}^{(*)}l^+l^-$ decay distributions allows to put new constraints on squark flavor violation. While the current sensitivity in C_{10} is about a factor of two away from MFV physics, beyond-CKM flavor mixing is strongly constrained, see Fig. 1. This concerns prominently left-right flavor mixing between the second and the third generation in the up-sector encoded in the parameter $(\delta_{23}^u)_{LR}$. With its sensitivity in other rare processes including $B_s - \bar{B}_s$ mixing and $b \rightarrow s\gamma$ modes being very weak, $(\delta_{23}^u)_{LR}$ has previously been bounded very loosely only.

We obtain – depending on the flavor-diagonal SUSY parameters – constraints as low as $(\delta_{23}^u)_{LR} \lesssim 0.1$. This excludes solutions to the flavor problem with RFV flavor models based on flavor generation in the up-sector and sub-TeV spectra. Models with horizontal flavor symmetries generically predict $(\delta_{23}^u)_{LR} \sim V_{cb}(m_t/m_{\tilde{q}})$, cf. e.g., [59] and are about an order of magnitude below the current limits. Note that in the future $(\delta_{23}^u)_{LR}$ could be probed in the presence of an appreciable first-third generation mixing in $K \rightarrow \pi\nu\bar{\nu}$ decays [60] at the NA62 experiment [61].

The new flavor constraints lead to predictions for b - and top physics:

- The $\bar{B}_s \rightarrow \mu^+\mu^-$ branching ratio is, assuming no scalar/pseudoscalar contributions, bounded from below, at about $\sim 1 \times 10^{-9}$, see Eq. (13). The constraint on the short-distance coupling C_{10} from the experimental upper limit Eq. (1) is consistent with the one obtained from semileptonic decay data. Both searches should be pursued further as they probe complementary NP.
- The forward-backward asymmetry in $\bar{B} \rightarrow \bar{K}^*l^+l^-$ decays has a zero at low dilepton mass. The position is near its SM value, consistent with the preliminary determination by the LHCb collaboration, see Eq. (2). The forward-backward asymmetry of the recently observed $\bar{B}_s \rightarrow \phi\mu^+\mu^-$ and $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$ decays shares the same features [62].

- Top FCNCs $t \rightarrow c\gamma, t \rightarrow cg, t \rightarrow cZ$ have branching ratios below $\lesssim \text{few} \times 10^{-8}, 10^{-6}$ and 10^{-7} , respectively, and are too small to be observed at the LHC with foreseeable luminosities.

The $|\Delta B| = |\Delta S| = 1$ constraints will improve in the near future with the large $b \rightarrow sl^+l^-$ -induced event samples expected from the LHC experiments. Progress arises from better statistics in combination with the availability of additional observables. We highlight here those sensitive to CP violation in C_{10} – induced by a complex-valued $(\delta_{23}^u)_{LR}$:

- The (naive) T-odd CP asymmetry $\langle A_7^D \rangle$ [44] can be up to order ten percent at small dilepton masses [13].
- The CP asymmetry $\langle a_{\text{CP}}^{(3)} \rangle$ does not require flavor tagging. At large dilepton masses it can reach a few percent [43].

The flavor constraints reported here get stronger for lighter stops, an ingredient of TeV-scale model building, recently, e.g., [63–66], with possibilities to be seen directly at the LHC. If realized in nature, chances are that such models or others based on the generic MSSM with light stops will show up one way or the other, or both.

Note added: During the publishing process a related and complementary work [67] on MFV SUSY constraints at large $\tan\beta$ from rare B -decay data appeared.

Acknowledgements

We are happy to thank Christoph Bobeth, Andreas Crivellin and Danny van Dyk for useful exchanges and Thomas Hahn and Sven Heinemeyer for **FeynHiggs** support. We are grateful to Gino Isidori for reminding us of the erratum to [49]. This work is supported in part by the *Bundesministerium für Bildung und Forschung (BMBF)* and the *German-Israeli Foundation for Scientific Research and Development (GIF)*. C. G. acknowledges support by the *Swiss National Science Foundation*. G.H. gratefully acknowledges the hospitality and stimulating atmosphere provided by the Aspen Center for Physics where parts of this work have been done. C. G. would like to thank the Physics Department at Boston University, where part of this work was done, for kind hospitality.

A Loop functions

We derived the dependence of $C_{7,9,10}$ on $(\delta_{23}^u)_{LR}$ in the MI approximation, cf. Eq. (7), from the exact expressions in [14]. We find the following loop functions:

$$F(x_1, x_2, x_{\tilde{t}_R}) = \frac{1}{6} \hat{x}_{av} \sum_{i=1,2} V_{i1} V_{i2}^* x_i^2 \frac{f_1(x_i/x_{\tilde{t}_R}) - f_1(x_i)}{x_i/x_{\tilde{t}_R} - x_i}, \quad (\text{A.1})$$

$$\begin{aligned} F^{Z-P}(\hat{x}_1, \hat{x}_2, \hat{x}_{\tilde{t}_R}) = \hat{x}_{av} \sum_{i,j=1,2} V_{j1} V_{i2}^* \Big\{ & U_{j1}^* U_{i1} \sqrt{\hat{x}_i \hat{x}_j} \frac{c_0(\hat{x}_{\tilde{t}_R}, \hat{x}_i, \hat{x}_j) - c_0(1, \hat{x}_i, \hat{x}_j)}{\hat{x}_{\tilde{t}_R} - 1} \\ & - 2V_{j1}^* V_{i1} \frac{c_2(\hat{x}_{\tilde{t}_R}, \hat{x}_i, \hat{x}_j) - c_2(1, \hat{x}_i, \hat{x}_j)}{\hat{x}_{\tilde{t}_R} - 1} \\ & + 2\delta_{ij} \frac{c_2(\hat{x}_j, 1, \hat{x}_{\tilde{t}_R}) - c_2(\hat{x}_j, 1, 1)}{\hat{x}_{\tilde{t}_R} - 1} \Big\}, \end{aligned} \quad (\text{A.2})$$

$$F^{\gamma-P}(\hat{x}_1, \hat{x}_2, \hat{x}_{\tilde{t}_R}) = \frac{1}{9} \hat{x}_{av} \sum_{i=1,2} V_{i1} V_{i2}^* \hat{x}_{\tilde{t}_R} \frac{\hat{x}_i/\hat{x}_{\tilde{t}_R} f_7(\hat{x}_i/\hat{x}_{\tilde{t}_R}) - \hat{x}_i f_7(\hat{x}_i)}{\hat{x}_i/\hat{x}_{\tilde{t}_R} - \hat{x}_i}, \quad (\text{A.3})$$

$$F^{\text{box}}(\hat{x}_1, \hat{x}_2, \hat{x}_{\tilde{t}_R}, \hat{x}_{\tilde{\nu}_1}) = 4\hat{x}_{av} \sum_{i,j=1,2} V_{i1} V_{i2}^* |V_{j1}|^2 \frac{d_2(\hat{x}_i, \hat{x}_j, \hat{x}_{\tilde{t}_R}, \hat{x}_{\tilde{\nu}_1}) - d_2(\hat{x}_i, \hat{x}_j, 1, \hat{x}_{\tilde{\nu}_1})}{\hat{x}_{\tilde{t}_R} - 1}, \quad (\text{A.4})$$

where

$$x_i = 1/\hat{x}_i = \frac{m_{\tilde{q}}^2}{m_{\tilde{\chi}_i}^2}, \quad (i = 1, 2), \quad x_{\tilde{t}_R} = 1/\hat{x}_{\tilde{t}_R} = \frac{m_{\tilde{q}}^2}{m_{\tilde{t}_R}^2}, \quad x_{\tilde{\nu}_1} = 1/\hat{x}_{\tilde{\nu}_1} = \frac{m_{\tilde{q}}^2}{m_{\tilde{\nu}_1}^2} \quad (\text{A.5})$$

and $\hat{x}_{av} = \frac{1}{6}(5 + \hat{x}_{\tilde{t}_R})$. The functions f_i, c_i, d_2 are defined in [14]. The unitary matrices U and V which appear above diagonalize the chargino mass matrix:

$$U^* M_{\tilde{\chi}^\pm} V^\dagger = \text{diag}(m_{\tilde{\chi}_1}, m_{\tilde{\chi}_2}), \quad (\text{A.6})$$

where

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2}m_W \sin \beta \\ \sqrt{2}m_W \cos \beta & \mu \end{pmatrix}. \quad (\text{A.7})$$

The up-squark mass matrix is parametrized as

$$M_{\tilde{u}}^2 = \begin{pmatrix} (M_{\tilde{u}}^2)_{LL} & (M_{\tilde{u}}^2)_{LR} \\ (M_{\tilde{u}}^2)_{LR}^\dagger & (M_{\tilde{u}}^2)_{RR} \end{pmatrix} \quad (\text{A.8})$$

with $(M_{\tilde{u}}^2)_{LL} = m_{\tilde{q}}^2 \mathbb{1}_{3 \times 3}$,

$$(M_{\tilde{u}}^2)_{LR} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & (\Delta_{23}^u)_{LR} \\ 0 & 0 & (\Delta_{33}^u)_{LR} \end{pmatrix}, \quad (M_{\tilde{u}}^2)_{RR} = \begin{pmatrix} m_{\tilde{q}}^2 & 0 & 0 \\ 0 & m_{\tilde{q}}^2 & 0 \\ 0 & 0 & m_{\tilde{t}_R}^2 \end{pmatrix}, \quad (\text{A.9})$$

with the diagonal elements $m_{\tilde{q}}^2$, $(\Delta_{33}^u)_{LR} = m_t (A_t - \mu \cot \beta)$ and $m_{\tilde{t}_R}^2$, defined as

$$m_{\tilde{t}_R}^2 = m_{\tilde{t}_R, \text{soft}}^2 + m_t^2 + \frac{2}{3} s_W^2 m_Z^2 \cos 2\beta, \quad (\text{A.10})$$

where $\tilde{m}_{\tilde{t}_R, \text{soft}}^2$ denotes the pure soft term contribution. The stop masses are obtained after diagonalization of $M_{\tilde{u}}^2$:

$$m_{\tilde{t}_{1,2}}^2 = \frac{1}{2} \left(m_{\tilde{q}}^2 + m_{\tilde{t}_R}^2 \mp \sqrt{\left(m_{\tilde{q}}^2 - m_{\tilde{t}_R}^2 \right)^2 + 4 (\Delta_{23}^u)_{LR}^2 + 4 (\Delta_{33}^u)_{LR}^2} \right). \quad (\text{A.11})$$

The other squark masses are then given as $m_{\tilde{q}}$.

Our findings for the Wilson coefficients $C_{7,9,10}$ agree with Ref. [16] if the following modifications are made to the results of Ref. [16]:

- 1.) Eqs. (25) and (26), (γ -penguin with chargino loop, contributions to C_9): $1/3P_{042}$ has to be replaced by $-1/3P_{042}$.
- 2.) Eq. (26), (γ -penguin with chargino loop, contributions to C_7): The complex conjugation of U_{i2} has to be removed.
- 3.) Eq. (31), (γ -penguin with gluino loop, contributions to C_7): The $(\delta_{23}^d)_{LL}$ contribution has to be multiplied by 2 and $(\delta_{23}^d)_{RL}$ has to be replaced by $-(\delta_{23}^d)_{LR}$.
- 4.) Eq. (34), (γ -penguin with chargino loop, case of light stop, contributions to C_9): The expression has to be multiplied by a factor $1/6$.

We explicitly checked the above corrections by direct calculations using the conventions of [14]. Note that the relative minus sign between [16] and [14] in front of $(\delta_{23}^d)_{LR}$ in the γ -penguin contribution to C_7 , see item 3., can be absorbed by a rephasing of the gluino mass and the A terms, or equivalently, by rephasing the right-chiral down squarks in the super-CKM basis. The corrections 1., 2. and 4. are in agreement with Ref. [68].

References

- [1] R. Aaij *et al.* [LHCb Collaboration], “Strong constraints on the rare decays $B_s \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$,” Phys. Rev. Lett. **108**, 231801 (2012) [arXiv:1203.4493 [hep-ex]].
- [2] M. Artuso *et al.*, “ B , D and K decays,” Eur. Phys. J. C **57**, 309 (2008) [arXiv:0801.1833 [hep-ph]].
- [3] G. Hiller, “The Pheno-analysis of $B \rightarrow K^{(*)} \mu^+ \mu^-$ decays in 2011 plus,” arXiv:1106.1547 [hep-ph], in the proceedings of Moriond EWK, March 13-20, 2011, La Thuile.
- [4] A. J. Buras, “Flavour Visions,” PoS BEAUTY **2011**, 008 (2011) [arXiv:1106.0998 [hep-ph]].

- [5] LHCb Collaboration, “Differential branching fraction and angular analysis of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay,” CERN-LHCb-CONF-2012-008.
- [6] C. Bobeth, G. Hiller, D. van Dyk and C. Wacker, “The Decay $B \rightarrow K l^+ l^-$ at Low Hadronic Recoil and Model-Independent $\Delta B = 1$ Constraints,” JHEP **1201**, 107 (2012) [arXiv:1111.2558 [hep-ph]].
- [7] M. Beneke, T. Feldmann and D. Seidel, “Exclusive radiative and electroweak $b \rightarrow d$ and $b \rightarrow s$ penguin decays at NLO,” Eur. Phys. J. C **41**, 173 (2005) [hep-ph/0412400].
- [8] A. Ali, G. Kramer and G.-h. Zhu, “ $B \rightarrow K^* l^+ l^-$ decay in soft-collinear effective theory,” Eur. Phys. J. C **47**, 625 (2006) [hep-ph/0601034].
- [9] C. Bobeth, G. Hiller and D. van Dyk, “The Benefits of $\bar{B} \rightarrow \bar{K}^* l^+ l^-$ Decays at Low Recoil,” JHEP **1007**, 098 (2010) [arXiv:1006.5013 [hep-ph]].
- [10] B. Grinstein and D. Pirjol, “Exclusive rare $B \rightarrow K^* \ell^+ \ell^-$ decays at low recoil: Controlling the long-distance effects,” Phys. Rev. D **70**, 114005 (2004) [hep-ph/0404250].
- [11] T. Aaltonen *et al.* [CDF Collaboration], “Measurements of the Angular Distributions in the Decays $B \rightarrow K^{(*)} \mu^+ \mu^-$ at CDF,” Phys. Rev. Lett. **108**, 081807 (2012) [arXiv:1108.0695 [hep-ex]].
- [12] LHCb Collaboration, “Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$,” CERN-LHCb-CONF-2011-038.
- [13] W. Altmannshofer, P. Paradisi and D. M. Straub, “Model-Independent Constraints on New Physics in $b \rightarrow s$ Transitions,” JHEP **1204** (2012) 008 [arXiv:1111.1257 [hep-ph]].
- [14] P. L. Cho, M. Misiak and D. Wyler, “ $K_L \rightarrow \pi^0 e^+ e^-$ and $B \rightarrow X_s \ell^+ \ell^-$ decay in the MSSM,” Phys. Rev. D **54**, 3329 (1996) [hep-ph/9601360].
- [15] J. L. Hewett and J. D. Wells, “Searching for supersymmetry in rare B decays,” Phys. Rev. D **55**, 5549 (1997) [hep-ph/9610323].
- [16] E. Lunghi, A. Masiero, I. Scimemi and L. Silvestrini, “ $B \rightarrow X_s l^+ l^-$ decays in supersymmetry,” Nucl. Phys. B **568**, 120 (2000) [hep-ph/9906286].
- [17] A. Ali, E. Lunghi, C. Greub and G. Hiller, “Improved model independent analysis of semileptonic and radiative rare B decays,” Phys. Rev. D **66**, 034002 (2002) [hep-ph/0112300].
- [18] A. Crivellin and U. Nierste, “Supersymmetric renormalisation of the CKM matrix and new constraints on the squark mass matrices,” Phys. Rev. D **79**, 035018 (2009) [arXiv:0810.1613 [hep-ph]].

- [19] A. Crivellin, L. Hofer, U. Nierste and D. Scherer, “Phenomenological consequences of radiative flavor violation in the MSSM,” *Phys. Rev. D* **84**, 035030 (2011) [arXiv:1105.2818 [hep-ph]].
- [20] M. S. Carena, D. Garcia, U. Nierste and C. E. M. Wagner, “ $b \rightarrow s\gamma$ and supersymmetry with large $\tan \beta$,” *Phys. Lett. B* **499**, 141 (2001) [hep-ph/0010003].
- [21] L. J. Hall, V. A. Kostelecky and S. Raby, “New Flavor Violations in Supergravity Models,” *Nucl. Phys. B* **267**, 415 (1986).
- [22] F. Gabbiani and A. Masiero, “FCNC in Generalized Supersymmetric Theories,” *Nucl. Phys. B* **322**, 235 (1989).
- [23] C. Bobeth, M. Misiak and J. Urban, “Photonic penguins at two loops and m_t dependence of $\text{BR}(B \rightarrow X_s l^+ l^-)$,” *Nucl. Phys. B* **574**, 291 (2000) [hep-ph/9910220].
- [24] EOS Collaboration, a code for flavor observables
<http://project.het.physik.tu-dortmund.de/eos/>
- [25] Tevatron Electroweak Working Group [CDF and D0 Collaboration], “Combination of CDF and D0 Results on the Mass of the Top Quark Using up to 5.6 fb^{-1} of Data,” arXiv:1007.3178 [hep-ex].
- [26] K. Nakamura *et al.* [Particle Data Group], “Review of particle physics,” *J. Phys. G* **37**, 075021 (2010).
- [27] P. Ball, S. Khalil and E. Kou, “ $B_s^0 - \bar{B}_s^0$ mixing and the $B_s \rightarrow J/\psi \phi$ asymmetry in supersymmetric models,” *Phys. Rev. D* **69**, 115011 (2004) [hep-ph/0311361].
- [28] G. Buchalla, G. Hiller and G. Isidori, “Phenomenology of nonstandard Z couplings in exclusive semileptonic $b \rightarrow s$ transitions,” *Phys. Rev. D* **63**, 014015 (2000) [hep-ph/0006136].
- [29] V. M. Abazov *et al.* [D0 Collaboration], “Search for scalar top quarks in the acoplanar charm jets and missing transverse energy final state in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$,” *Phys. Lett. B* **665**, 1 (2008) [arXiv:0803.2263 [hep-ex]].
- [30] T. Aaltonen *et al.* [CDF Collaboration], “Search for the supersymmetric partner of the top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$,” *Phys. Rev. D* **82**, 092001 (2010) [arXiv:1009.0266 [hep-ex]].
- [31] ATLAS Collaboration, “Search for Scalar Top Quark Pair Production in Natural Gauge Mediated Supersymmetry Models with the ATLAS Detector in pp Collisions at $\sqrt{s} = 7 \text{ TeV}$,” ATLAS-CONF-2012-036 (2012).
- [32] CMS Collaboration, “Search for new physics in events with same-sign dileptons, b -tagged jets and missing energy,” CMS-PAS-SUS-11-020 (2012).

- [33] S. Heinemeyer, W. Hollik and G. Weiglein, “FeynHiggs: A Program for the calculation of the masses of the neutral CP even Higgs bosons in the MSSM,” *Comput. Phys. Commun.* **124**, 76 (2000) [hep-ph/9812320].
- [34] S. Heinemeyer, W. Hollik and G. Weiglein, “The Masses of the neutral CP - even Higgs bosons in the MSSM: Accurate analysis at the two loop level,” *Eur. Phys. J. C* **9**, 343 (1999) [hep-ph/9812472].
- [35] G. Degrandi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, “Towards high precision predictions for the MSSM Higgs sector,” *Eur. Phys. J. C* **28**, 133 (2003) [hep-ph/0212020].
- [36] M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, “The Higgs Boson Masses and Mixings of the Complex MSSM in the Feynman-Diagrammatic Approach,” *JHEP* **0702**, 047 (2007) [hep-ph/0611326].
- [37] G. Aad *et al.* [ATLAS Collaboration], “Combined search for the Standard Model Higgs boson using up to 4.9 fb⁻¹ of pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC,” *Phys. Lett. B* **710**, 49 (2012) [arXiv:1202.1408 [hep-ex]].
- [38] S. Chatrchyan *et al.* [CMS Collaboration], “Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV,” *Phys. Lett. B* **710**, 26 (2012) [arXiv:1202.1488 [hep-ex]].
- [39] M. Arana-Catania, S. Heinemeyer, M. J. Herrero and S. Penaranda, “Higgs Boson masses and B-Physics Constraints in Non-Minimal Flavor Violating SUSY scenarios,” *JHEP* **1205**, 015 (2012) [arXiv:1109.6232 [hep-ph]].
- [40] Z. -j. Xiao, F. -g. Li and W. -j. Zou, “ $B \rightarrow X(s)\gamma, X(s)l^+l^-$ decays and constraints on the mass insertion parameters in the MSSM,” *Commun. Theor. Phys.* **46**, 687 (2006) [hep-ph/0603120].
- [41] J. A. Casas and S. Dimopoulos, “Stability bounds on flavor violating trilinear soft terms in the MSSM,” *Phys. Lett. B* **387**, 107 (1996) [hep-ph/9606237].
- [42] J.-h. Park, “Metastability bounds on flavour-violating trilinear soft terms in the MSSM,” *Phys. Rev. D* **83**, 055015 (2011) [arXiv:1011.4939 [hep-ph]].
- [43] C. Bobeth, G. Hiller and D. van Dyk, “More Benefits of Semileptonic Rare B Decays at Low Recoil: CP Violation,” *JHEP* **1107**, 067 (2011) [arXiv:1105.0376 [hep-ph]].
- [44] C. Bobeth, G. Hiller and G. Piranishvili, “CP Asymmetries in $\bar{B} \rightarrow \bar{K}^*(\rightarrow \bar{K}\pi)\bar{\ell}\ell$ and Untagged $\bar{B}_s, B_s \rightarrow \phi(\rightarrow K^+K^-)\bar{\ell}\ell$ Decays at NLO,” *JHEP* **0807**, 106 (2008) [arXiv:0805.2525 [hep-ph]].

- [45] K. de Bruyn, R. Fleischer, R. Kneijens, P. Koppenburg, M. Merk, A. Pellegrino and N. Tuning, “Probing New Physics via the $B_s^0 \rightarrow \mu^+ \mu^-$ Effective Lifetime,” Phys. Rev. Lett. **109**, 041801 (2012) [arXiv:1204.1737 [hep-ph]].
- [46] E. Gamiz, C. T. H. Davies, G. P. Lepage, J. Shigemitsu and M. Wingate [HPQCD Collaboration], “Neutral B Meson Mixing in Unquenched Lattice QCD,” Phys. Rev. D **80** (2009) 014503, [arXiv:0902.1815 [hep-lat]].
- [47] J. Simone *et al.* [Fermilab Lattice and MILC Collaborations], “The decay constants $f(D/s)$, $f(D^+)$, $f(B/s)$ and $f(B)$ from lattice QCD,” PoS **LATTICE2010** (2010) 317.
- [48] S. Weinberg, “Electromagnetic and weak masses,” Phys. Rev. Lett. **29**, 388 (1972).
- [49] G. Colangelo and G. Isidori, “Supersymmetric contributions to rare kaon decays: Beyond the single mass insertion approximation,” JHEP **9809**, 009 (1998) [hep-ph/9808487].
- [50] A. J. Buras, G. Colangelo, G. Isidori, A. Romanino and L. Silvestrini, “Connections between epsilon-prime / epsilon and rare kaon decays in supersymmetry,” Nucl. Phys. B **566**, 3 (2000) [hep-ph/9908371].
- [51] M. Ciuchini *et al.*, “Delta M(K) and epsilon(K) in SUSY at the next-to-leading order,” JHEP **9810** (1998) 008 [hep-ph/9808328].
- [52] A. J. Buras, S. Jager and J. Urban, “Master formulae for Delta F=2 NLO QCD factors in the standard model and beyond,” Nucl. Phys. B **605**, 600 (2001) [hep-ph/0102316].
- [53] G. Colangelo *et al.*, “Review of lattice results concerning low energy particle physics,” Eur. Phys. J. C **71**, 1695 (2011) [arXiv:1011.4408 [hep-lat]].
- [54] J. A. Aguilar-Saavedra and B. M. Nobre, “Rare top decays $t \rightarrow c\gamma$, $t \rightarrow cg$ and CKM unitarity,” Phys. Lett. B **553** (2003) 251 [hep-ph/0210360].
- [55] J. A. Aguilar-Saavedra, “Top flavor-changing neutral interactions: Theoretical expectations and experimental detection,” Acta Phys. Polon. B **35**, 2695 (2004) [arXiv:hep-ph/0409342].
- [56] J. J. Cao, G. Eilam, M. Frank, K. Hikasa, G. L. Liu, I. Turan and J. M. Yang, “SUSY-induced FCNC top-quark processes at the large hadron collider,” Phys. Rev. D **75** (2007) 075021 [hep-ph/0702264].
- [57] F. M. A. Veloso, “Study of ATLAS sensitivity to FCNC top quark decays,” CERN-THESIS-2008-106.
- [58] G. M. de Divitiis, R. Petronzio and L. Silvestrini, “Flavour changing top decays in supersymmetric extensions of the standard model,” Nucl. Phys. B **504**, 45 (1997) [arXiv:hep-ph/9704244].

- [59] Y. Nir and G. Raz, “Quark squark alignment revisited,” *Phys. Rev. D* **66**, 035007 (2002) [hep-ph/0206064].
- [60] G. Isidori, F. Mescia, P. Paradisi, C. Smith and S. Trine, “Exploring the flavour structure of the MSSM with rare K decays,” *JHEP* **0608**, 064 (2006) [hep-ph/0604074].
- [61] T. Spadaro [For the NA62 Collaboration], “The NA62 experiment at CERN: status and perspectives,” arXiv:1101.5631 [hep-ex].
- [62] G. Hiller and A. Kagan, “Probing for new physics in polarized Lambda(b) decays at the Z,” *Phys. Rev. D* **65**, 074038 (2002) [hep-ph/0108074].
- [63] M. Papucci, J. T. Ruderman and A. Weiler, “Natural SUSY Endures,” arXiv:1110.6926 [hep-ph].
- [64] C. Csaki, L. Randall and J. Terning, “Light Stops from Seiberg Duality,” arXiv:1201.1293 [hep-ph].
- [65] N. Craig, M. McCullough and J. Thaler, “The New Flavor of Higgsed Gauge Mediation,” *JHEP* **1203**, 049 (2012) [arXiv:1201.2179 [hep-ph]].
- [66] N. Craig, M. McCullough and J. Thaler, “Flavor Mediation Delivers Natural SUSY,” *JHEP* **1206**, 046 (2012) [arXiv:1203.1622 [hep-ph]].
- [67] F. Mahmoudi, S. Neshatpour and J. Orloff, “Supersymmetric constraints from $B_s \rightarrow \mu^+ \mu^-$ and $B \rightarrow K^* \mu^+ \mu^-$ observables,” arXiv:1205.1845 [hep-ph].
- [68] E. Gabrielli, K. Huitu and S. Khalil, “Comparative study of CP asymmetries in supersymmetric models,” *Nucl. Phys. B* **710**, 139 (2005) [hep-ph/0407291].